Energy Deposition Issues in VLHC

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Outline

- Beam losses
  - Define class of losses
  - Quench levels
  - Loss / Quench levels $\longrightarrow$ Excess loss factor
- Collimation
  - Tentative specification and optics
  - Efficiency calculation
  - Ring Aperture considerations
  - Experimental results at 120 Gev
- Downstream of experiments beyond focusing quadrupoles
- Conclusions

Class of Losses

- Single Pass, hard local losses
  - kicker errors, injection mismatch or dump failures. Need (sometimes heavy) dumps. Not discussed here.
- Momentum losses at ramping
- Inelastic interactions (beam gas & collision)
- Elastic interactions (beam gas & collision)
- Dynamic losses

Losses at ramping

- Off-bucket protons are not accelerated (phase error & longitudinal diffusion)
- Their δ_p decreases continuously
- A flash of losses occurs soon after the beginning of the ramp
- The duration of the flash is between 1s and 1mn (depends on $\dot{B}/B$)

Consider 3% of a store to lie outside the buckets. Then the intensity of the flash would be

$$\Delta N_{\overline{RF}} = \begin{cases} 5 \times 10^{12} \text{ protons} & \text{High B} \\ 4 \times 10^{13} \text{ protons} & \text{Low B} \end{cases} \tag{1}$$

Inelastic Interactions : pp in collision

Power deposition is

$$P = E_{proton} \times \mathcal{L} \times \sigma_{inelastic} = 5\ 10^{13} \times 1.6\ 10^{-19} \times 10^{34} \times 1.3\ 10^{-25} \quad (2)$$

$$= 10^{4}\ \ \mathrm{Watt} \quad (3)$$

Most of this power goes in the triplet of quadrupoles on each side of the experiment. Need protective shielding and specific R&D for the quadrupoles.

Not discussed here.

Inelastic Interactions : p-Residual Gas along the ring

- Cold machine with beam screen: (LHC after some clean-up time by SR)

$$\rho_{Ox-equ} = 6\,10^7 \text{ atoms cm}^{-3} <=> p = 1.7\,10^{-9}\ \text{Torr}_{warm\ equ.} \tag{4}$$

$$\mathcal{L}_{bg} = N_p \rho_{gas} c = 1.8\,10^{32}\,\text{cm}^{-2}\text{s}^{-1} <=> \tau = 400\text{hr} \ \text{ with}\,\sigma_{p-Ox} = 0.5\,\text{barn} \tag{5}$$

- Warm machine, baked and without SR : $p = 3\,10^{-11}$ Torr

  With SR, VLHC estimation :

$$p = 3\,10^{-10}\ \text{Torr} <=> \tau = 2000\text{hr} \tag{6}$$

Full ring integrated:

$$\dot{N}_{bg} = N_{stored}/\tau = \begin{cases} 10^{14}/1.3\,10^6 \ \sim 10^8 \text{p/s} & \text{High B} \\ 1.2\,10^{15}/7\,10^6 \sim 2\,10^8 \text{p/s} & \text{Low B} \end{cases} \tag{7}$$

Loss rate per meter of vacuum chamber are $\dot{n}_{bg} \leq 10^3 \text{p/m/s}$. Local power deposition is therefore $p \leq 8$ mW/m.

Elastic Interactions

pp in collision Differential cross-section $d\sigma/dt \sim \exp(-bt) \sim \exp(-\theta^2/\theta_o^2)$

With $b = 20$ Gev^{-2}, $\theta_o = 5$ μrad, to be compared to the beam divergence at the collision point $\sigma'^* = 10$ μrad.

$\overline{\theta_{pp}} < \sigma'^*$ $<=>$ protons are recycled, no harm

p-Residual Gas With $b_{p-Ox} = 90$ Gev^{-2}, $\theta_o = 2$ μrad, while $\sigma'_{arc} = 0.3$ μrad. With $\overline{\theta_{pp}}/\sigma'_{arc} = 7$, scattered protons feed the halo (delayed losses). Rates are obtained with $\sigma_{el} = \sigma_{tot}/3 = 140$ mb and $\dot{N}_{bg} = \mathcal{L}_{bg}\sigma_{el}$.

$$\dot{N}_{bg} = \begin{cases} 4 \times 10^7 \text{ p/s} & \text{High B} \\ 7 \times 10^7 \text{ p/s} & \text{Low B} \end{cases} \tag{8}$$

Dynamic losses

- Not really predictable – related to dynamic aperture and beam-beam control
- Use operational approach: adjust N_{stored} such that

$$\dot{N}_{dyn} \leq \dot{N}_{collision} = 2\mathcal{L}_{nominal}\sigma_{pp} = 2.6 \times 10^9 \text{ p/s} \tag{9}$$

- (Otherwise said: a good high luminosity pp collider is a collider which satisfies this condition)

Summary for Losses

1. **Single Pass/local losses** $=>$ Local dumps
2. **Transient Losses** Mostly $\overline{RF}$ at injection energy

$$\Delta N_{\overline{RF}} = \begin{cases} 5 \times 10^{12}\ \mathrm{p} & \text{High B} \\ 4 \times 10^{13}\ \mathrm{p} & \text{Low B} \end{cases} \tag{10}$$

$=>$ MOMENTUM COLLIMATION

3. **Steady Losses in collision**

a) $P = 10$kW on each triplet. Need protection + R&D for triplet quadrupoles

b) Dynamic + (beam gas losses)

$$\dot{N} = \dot{N}_{dyn}\dot{N}_{bg} \approx 3 \times 10^{9}\ \mathrm{p/s} \quad \text{High \& Low B} \tag{11}$$

$=>$ BETATRON COLLIMATION

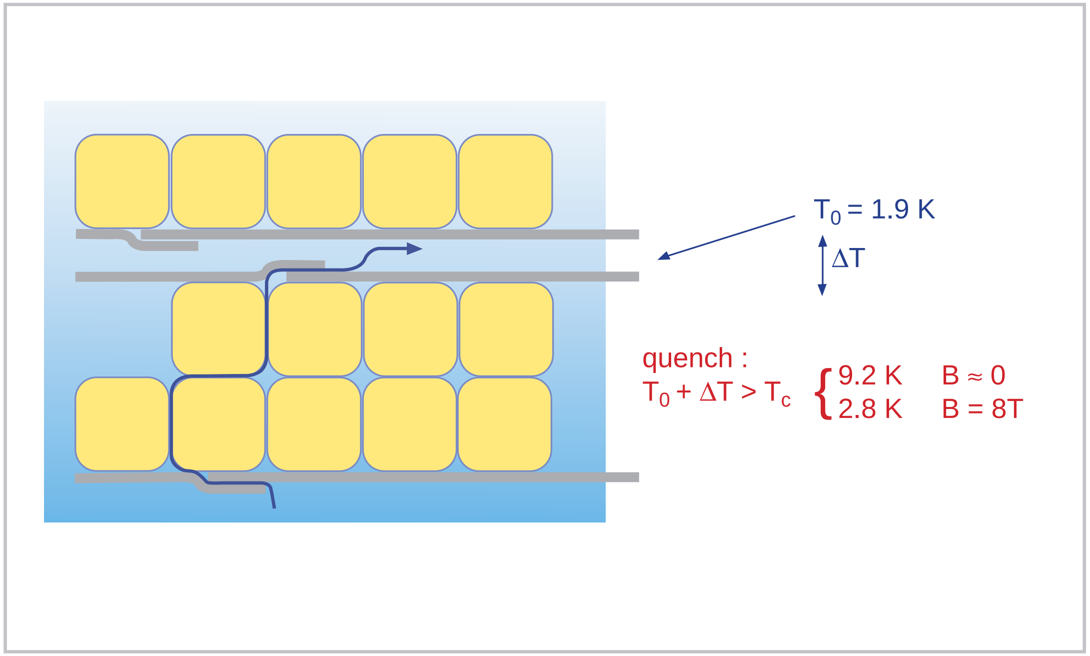
Further discuss 2) and 3b)

Quench levels and beam losses

- QUENCH : local energy ΔQ_q(transient case) or power deposition W_q heat the coil up to the critical temperature T_c.
- Estimate ΔQ_q $[\mathrm{Jcm}^{-3}]$ and W_q $[\mathrm{Wcm}^{-3}]$
- Simulate the map of energy deposition of a proton impacting the vacuum at grazing angle. Extract the largest value $\hat{\epsilon}$ $[\mathrm{J(m)cm}^{-3}]$ in the coil (taking into account the effective shower length $L_{shower} \sim 1$ m in case of longitudinally distributed losses).
- Convert quench power or energy to a number of protons (per meter) to quench

$$\Delta N_q = \frac{\Delta Q_q}{\hat{\epsilon}} \quad or \quad \dot{N}_q = \frac{W_q}{\hat{\epsilon}} \tag{12}$$

Superconducting cable – schematic – see next slide



Quench limits in NbTi coils - LHC values

- **Transient:**
  Limit given by the static heat reserve inside the conductor. For $\tau_{loss} > 0.1$ s, contribution of the trapped helium can be taken into account.

  ΔQ_q is obtained by integrating the heat capacity of the coil components

- **Continuous:**
  Heat transfer across the insulation of the conductor for $T \leq T_c$ – Need measurements on prototype coils

	Quench Limit		
3 TeV	$\Delta Q_q = 0.35$	$[\mathrm{J\ cm}^{-3}]$	TRANSIENT
50 TeV	$W_q = 5.0\ 10^{-3}$	$[\mathrm{W\ cm}^{-3}]$ (Saclay)	CONTINUOUS

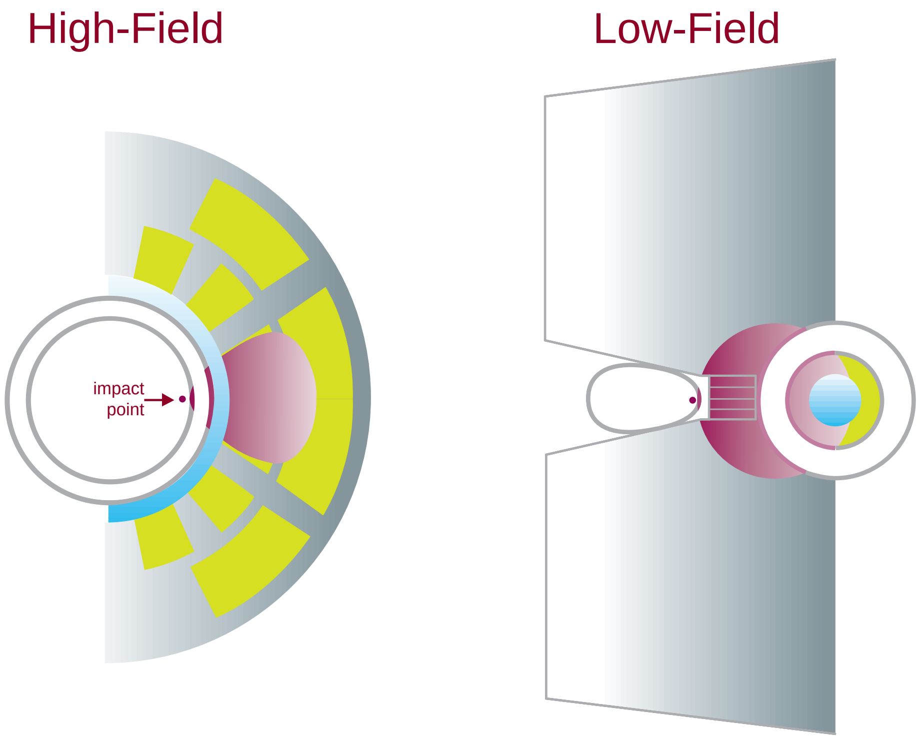
Peak energy deposition $\hat{\epsilon}$ per proton in the coil of LHC type magnets $\equiv$ High B VLHC

- Impact of primary proton of energy E at betatronic angle
- CASIM simulation at .45 and 7 TeV
- Inter-Extrapolation LHC $\rightarrow$ VLHC with $\hat{\epsilon} \sim E \ln 5.2E$ (need new simulation)

Beam energy E $[\mathrm{TeV}]$	Peak energy density $\hat{\epsilon}$ $[\mathrm{J\ m\ cm}^{-3}]$	Relative peak density $\hat{\epsilon}/\hat{\epsilon}(.45)$ TeV
.45	0.14×10^{-10}	1
3	3.0×10^{-10}	21
7	9.2×10^{-10}	67
50	100×10^{-10}	730

In the low-field option, the energy deposition $\hat{\epsilon}$ per proton in the coil is smaller (see next slide). From N.Mokhov : $\hat{\epsilon}(3\ \mathrm{TeV}) = 4.2 \cdot 10^{-12}$ Jcm^{-3}m. At collision low-B $\equiv$ high-B (see slide 26).

Tranverse shower in two kinds of magnets - schematic



In the high-field magnet, the coil is near the impact point, while in the low-field magnet, the insert holding the upper and the lower halves of the yoke makes an efficient protection.

Compute an excess loss factor

- $$l_f = \frac{\Delta N_{loss}}{\Delta N_q} \quad \text{and} \quad \frac{\dot{N}_{loss}}{\dot{N}_q} \tag{13}$$
- Consider $\overline{RF}$ at ramping at the worst case at injection
- Consider steady losses at collision as the sole case (see below for margin factors)
- In both case $n_{turns}^{loss} \gg 1 \quad => $ losses concentrate at a few aperture limitations
- Use $\quad few \equiv 1$ (slightly conservative)

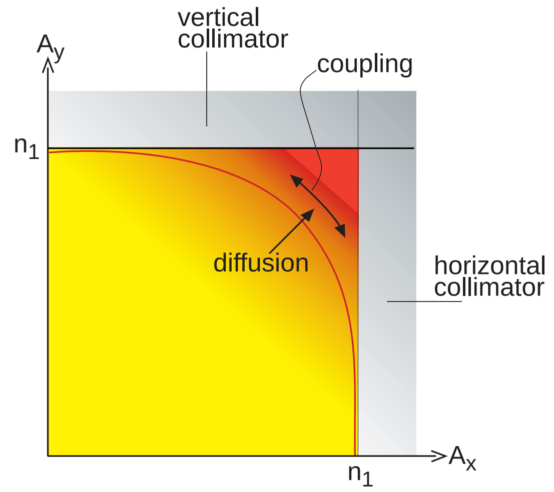
	protons s^{-1}	protons $s^{-1}(m^{-1})$	l_f
Injection - Low B	$\Delta N_{\overline{RF}} = 4\ 10^{13}$	$\Delta N_q = 7\ 10^{10}$	600
Injection - High B	$\Delta N_{\overline{RF}} = 5\ 10^{12}$	$\Delta N_q = 1.2\ 10^{9}$	4000
Collision	$\dot{N}_{loss} = 3\ 10^{9}$	$\dot{N}_q = 5\ 10^{5}$	6000

Clear need for collimation – betatronic and momentum

Basic arguments for Proton Collimation

- Halo protons migrate slowly (transverse or longitudinal)
  $\longrightarrow$ A localised interception system will therefore do the job
- Need approximate circular primary collimation (norm.coord), see next slide
- Slow migration $\equiv$ small impact parameters.
  Outscattered fraction is large ($\sim 30\%$)
  $\longrightarrow$ Therefore need secondary collimators
- Aperture is expensive
  Shall not waste it with a large secondary halo

Collimation without skew: loss fluctuations



In a perfectly decoupled optics, transverse diffusion by amplitude growth is dominantly radial in the plane of (invariant-)amplitudes $A_x - A_y$. Whenever coupling sets-up, the area between the circle and the square is emptied during $\tau_{coupling}$. These fluctuations of losses are avoided by using a skew primary collimator in addition to H and V ones.

Specification for Betatron collimation

- With primary collimators at depth $n_1\sigma_\beta$ and secondary at $n_2\sigma_\beta$, keep the size of the secondary halo $A_{sec} \approx n_2$
- With nearly isotropic scattering at the primary collimator, need several secondary/primary.
- Realistic compromise is 3 primaries and 12 secondaries
- Need an insertion which satisfies different correlated phase advances for each pair primary-secondary
- Such an insertion provides $A_{sec} \leq 7.6$ with $n_2 = 7$
  (H & V only: $A_{sec} = 8.5$, H & V and optics not optimised : $A_{sec} > 10$)

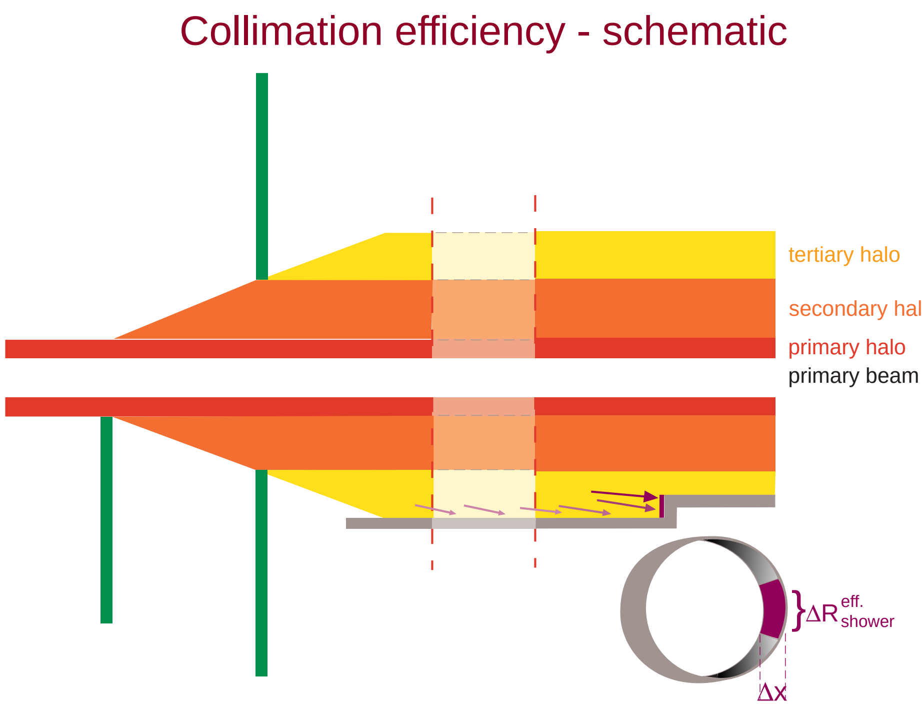
Table 1: Correlated phase advances μ_x and μ_y and $X - Y$ jaw orientations α_{Jaw} for three primary jaw orientations α and four scattering angles ϕ . $\mu_o = \cos^{-1}(n_1/n_2)$.

α	ϕ	μ_x	μ_y	α_{Jaw}	
0	0	μ_o	-	0	mom. coll.
0	π	$\pi - \mu_o$	-	0	mom. coll.
0	$\pi/2$	π	$3\pi/2$	μ_o	mom. coll.
0	$-\pi/2$	π	$3\pi/2$	-μ_o	mom. coll.
$\pi/4$	$\pi/4$	μ_o	μ_o	$\pi/4$	
$\pi/4$	$5\pi/4$	$\pi - \mu_o$	$\pi - \mu_o$	$\pi/4$	
$\pi/4$	$3\pi/4$	$\pi - \mu_o$	$\pi + \mu_o$	$\pi/4$	
$\pi/4$	$-\pi/4$	$\pi + \mu_o$	$\pi - \mu_o$	$\pi/4$	
$\pi/2$	$\pi/2$	-	μ_o	$\pi/2$	
$\pi/2$	$-\pi/2$	-	$\pi - \mu_o$	$\pi/2$	
$\pi/2$	π	$\pi/2$	π	$\pi/2 - \mu_o$	
$\pi/2$	0	$\pi/2$	π	$\pi/2 + \mu_o$	

Betatron Collimation - Spec. continued

- Such an optics yet to be studied
- Needs a straight section with $\Delta\mu_{x,y} \simeq 4 - 6\pi$
  (In LHC , limited to $\sim 2\pi \rightarrow A_{sec} = 8.6$)
- At 50 TeV , $\sigma_\beta \simeq 0.07$ mm, while CO do not scale with energy.
  Shall expect $\mathrm{CO}_{rms} \approx 0.5$ mm and $\mathrm{CO}_{peak} > 2$ mm
- $\rightarrow$ A dynamic closed orbit control at ≤ 0.01 mm is therefore mandatory in collimation insertions
- Needs warm or superferric magnets (Power deposition is several kWatts)

COLLIMATION - EFFICIENCY CALCULATION (K2 code)



At the left, a primary jaw, followed by two secondary ones (many of each in a real case, see slide 19). The inefficiency is obtained by integrating the tertiary halo at an aperture limitation made by a welding offset of the pipe ($\Delta_x = 1$ mm). The aperture at the step is a variable.

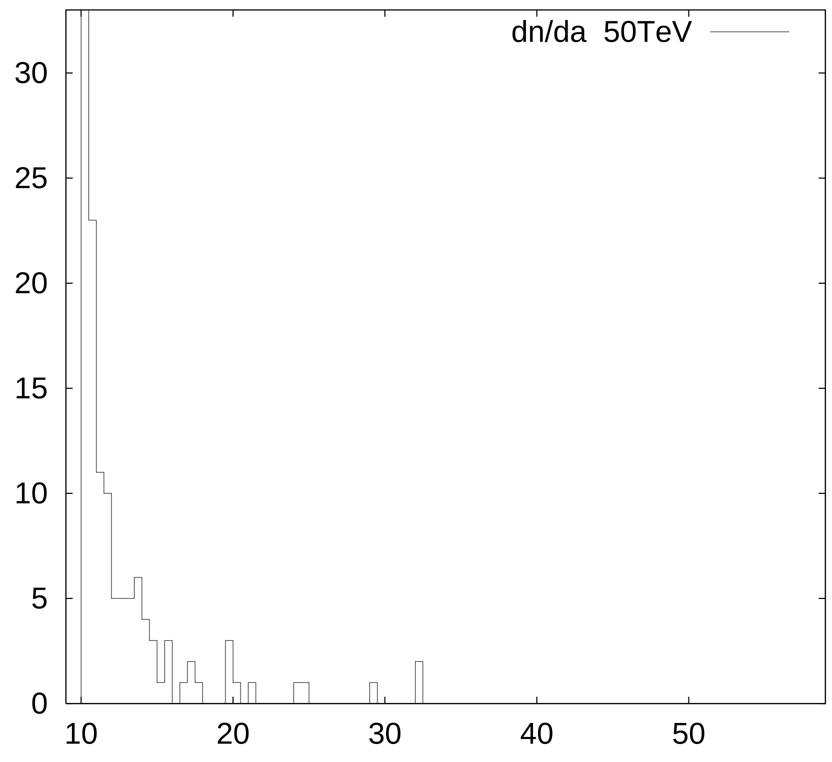
COLLIMATION EFFICIENCY CALCULATION (K2 code)

- pA, pp & pn Elastic and Single Diff. Scattering, Rutherford & m.c.s in collimators
- Multiturn tracking until absorption, in a collimator or at a variable aperture limitation A_{ring}
- Get 4D-tertiary halo density at $\geq A_{ring}$ as $\rho(A_x, A_y, \mu_x, \mu_y) = \frac{1}{N_{halo}} \frac{d^4 N}{dA_x dA_y \mu_x \mu_y}$
- Compute the acceptance of a vacuum chamber step (used $\Delta_x = 1$ mm) $a(A_x, A_y, \mu_x, \mu_y)$
- Get a relative loss rate ($\equiv$ inefficiency) $\eta_{coll} = \int\int\int\int_{A_{ring}}^{\infty} \rho(A_x, A_y, \mu_x, \mu_y) a(A_x, A_y, \mu_x, \mu_y) dA_x dA_y d\mu_x d\mu_y$
- Use $n_1 = 6$, $n_2 = 7$ (with LHC emmitance)

Tertiary normalised amplitude distribution at 50 TeV

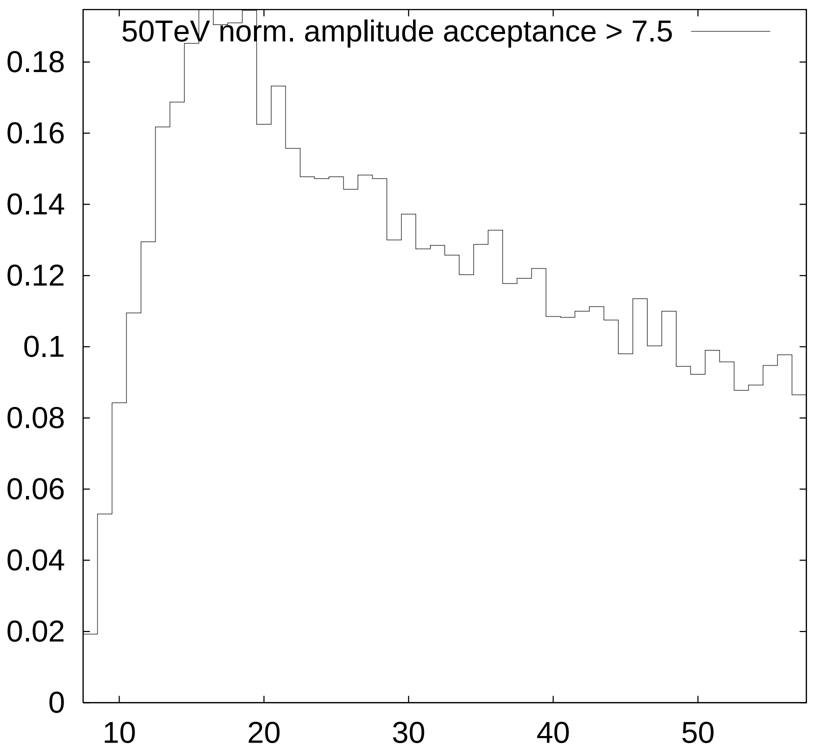
Used LHC betatron collimation insertion (nearly optimum)

Relative Integral : 123/500'000 = 2.5e-4

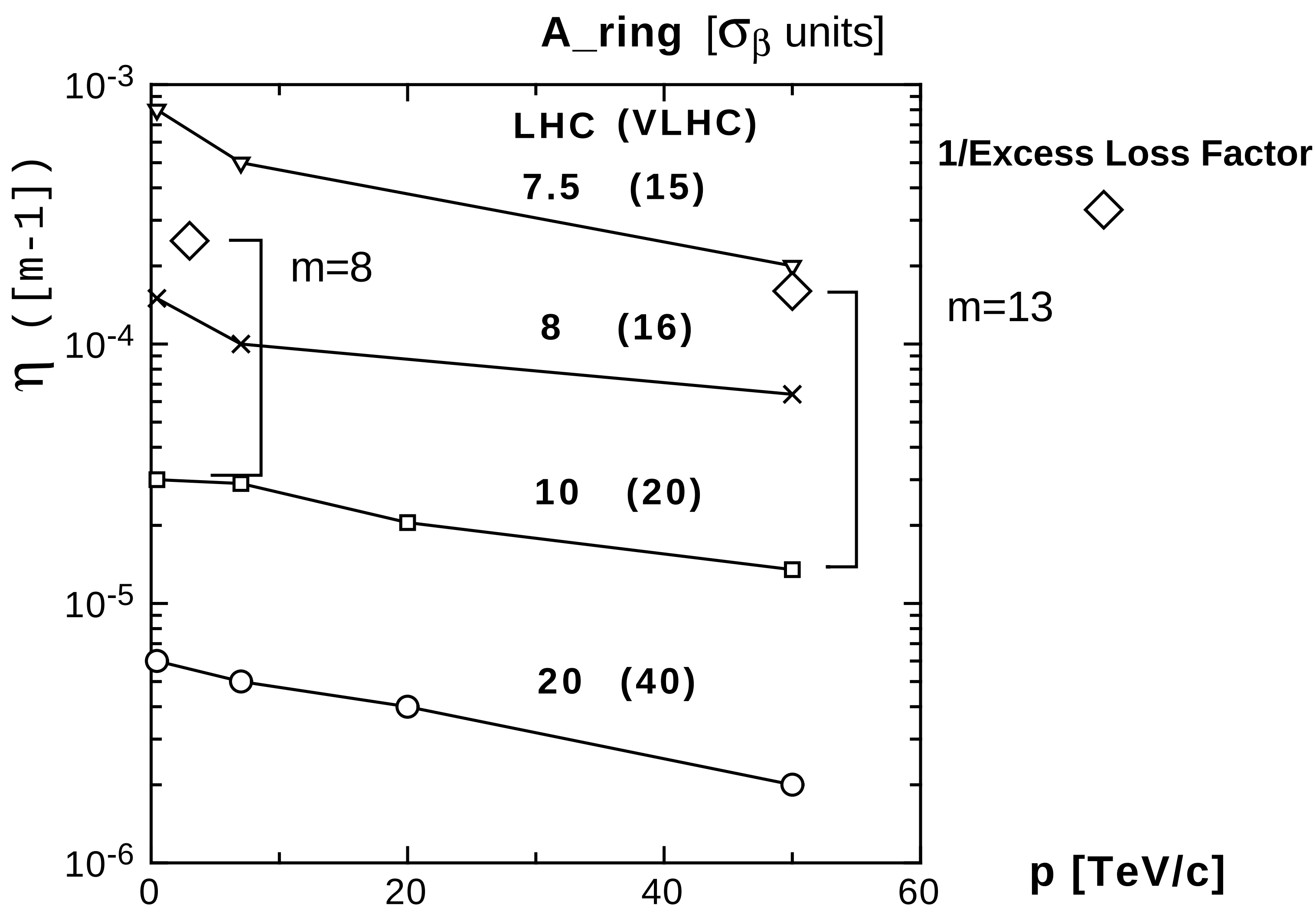


($\theta_{mcs}(1\lambda_{Cu}) = 0.9$ μrad, $\theta_0^{el} = 2\mu$rad, $\sigma'_{arc} = 0.3$ μrad)

Normalised amplitude acceptance of a pipe step (1mm) at 50 TeV



COLLIMATION EFFICIENCY – RESULTS

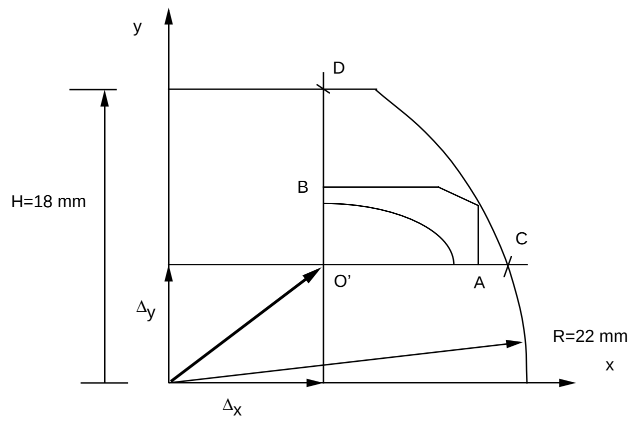


Estimated Margins at $A_{ring} = 20$ (VLHC σ_β units)

Beam Energy	Margin Factor $m = \frac{1}{\eta l_f}$	
3 TeV	50	Low Field option
3 TeV	8	High Field option
50 TeV	13	

- At 50 TeV, the aperture limitation will most likely be in experimental insertions, not in the arcs, therefore low-B/high-B machines have similar limits.
- Margins are > 1 but not high. At 50 TeV at least, good margin is mandatory to absorb fluctuations of losses around average.
- $\longrightarrow$ Need optimum collimation insertion.
- $\longrightarrow$ Need careful aperture specification and studies.

Geometrical Aperture (LHC dipoles)



$$\Delta_{x,y} = CO_{peak} + TOL_{mech.+align} + D\cdot\delta_p + (d_{sep}) = \sim 3 + \sim 3 + \sim 4 \approx 10\,\mathrm{mm} \tag{14}$$

VLHC :

3 TeV : $20\sigma_\beta \simeq 6$ mm

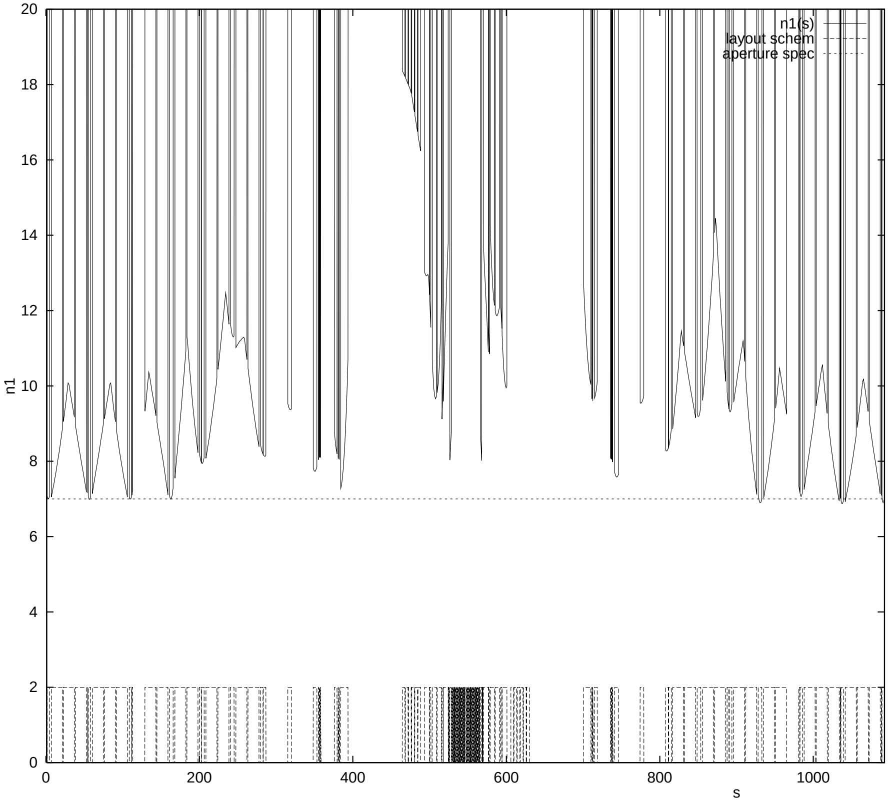
50 TeV : $20\sigma_\beta \simeq 1.4$ mm

→ **Aperture Dominated by Geometry**

→ **Choose normalised aperture with adequate margin**

→ **Fix total margin in mm ?**

Normalised primary aperture $n_1(s)$ in collision insertion at injection

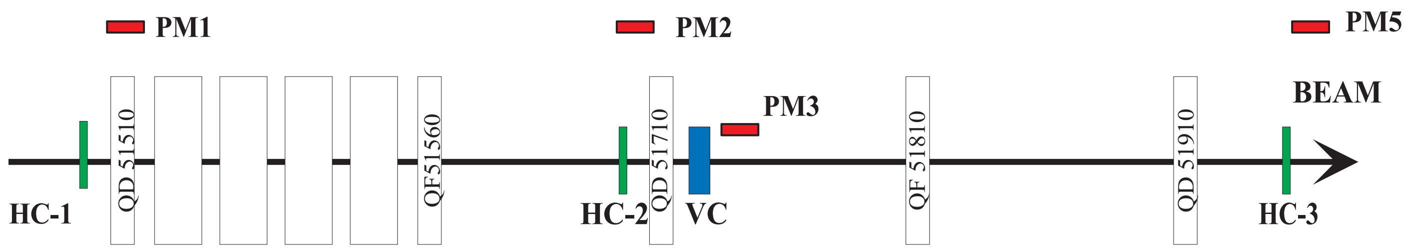


Systematically used in optics studies and matching

(A remark about VLHC/LHC normalised quantities)

- LHC normalised emittance : $\epsilon_n = 3.75\ \mu\mathrm{m}$
- VLHC normalised emittance: $\epsilon_n = 1\ \mu\mathrm{m}$
- While collective effects (say beam-beam) scale with $\sigma_\beta \sim \sqrt{\epsilon}$, magnetic errors do not
- Must be careful in comparisons between the two projects

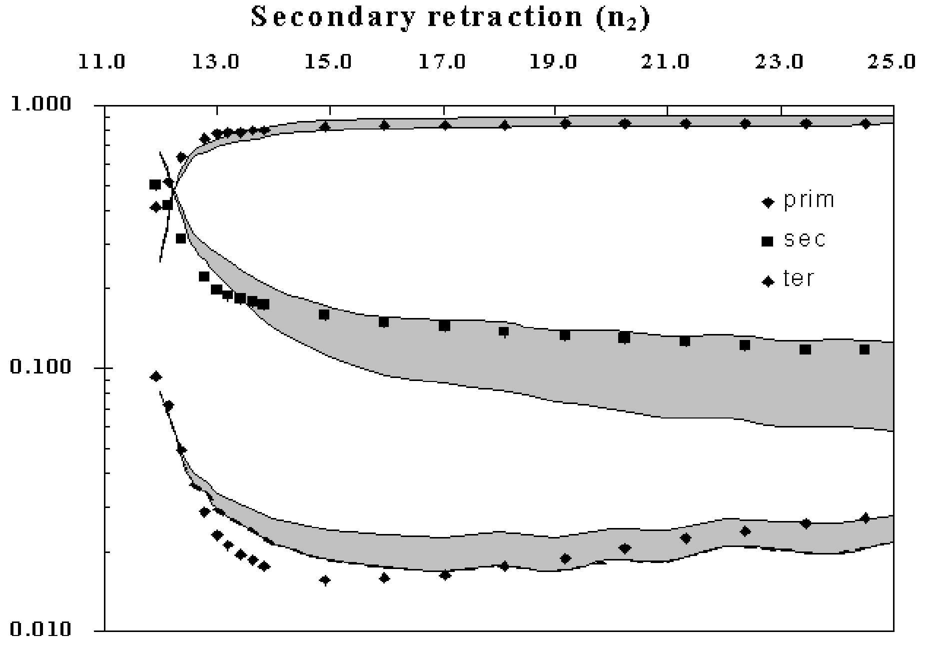
A collimation experiment at 120 GeV in the SPS



- Three horizontal collimators (HC-i) (PRIM-SEC-TER) + One vertical
- 120 GeV coasting beam made to diffuse with noise in a damper
- Measurement of the inelastic rates in all collimator with scintillators
- Fix $n_1 = 12$ (PRIM) , $n_3 = 18$ (TER - Simulates a ring aperture limitation)
- Vary $n_2 = [12, 25]$ (SEC)
- Compare to K2 (+GEANT) simulations

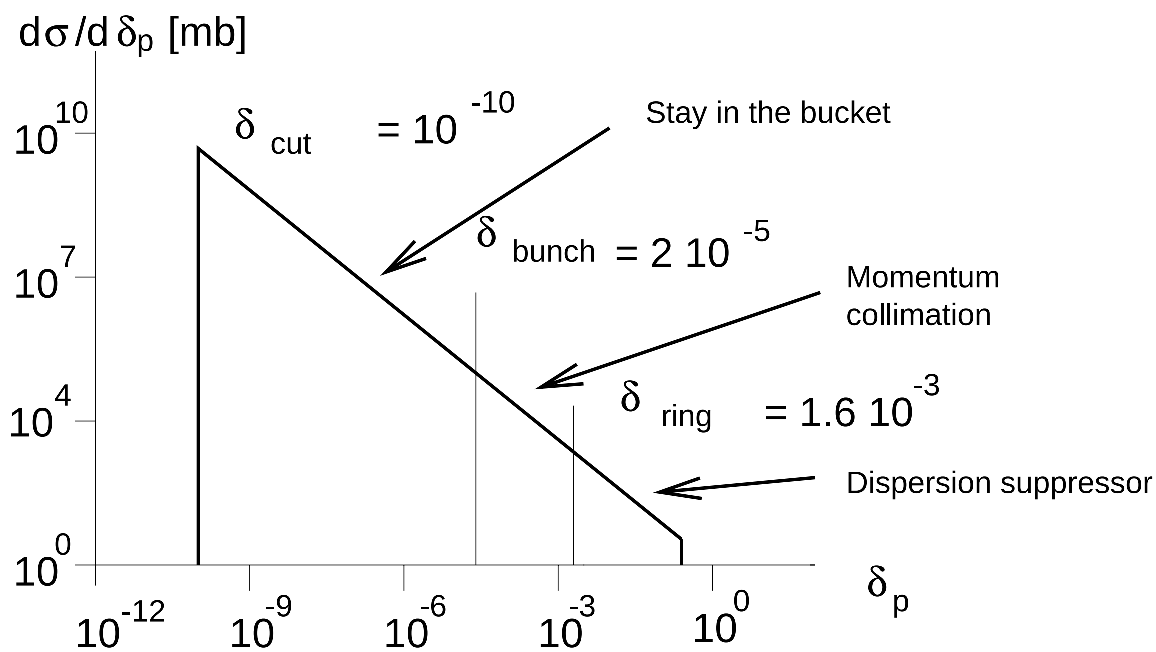
Experiment at 120 GeV – Results

- Dots : data , Grey areas : K2 simulation, $n_1 = 12$, $n_3 = 18$, $\epsilon_n = 3.75\ \mu$m
- Multiturn effect clearly visible
- Worst relative difference data/simulation : 40%



Thesis of Nuria Catalan Lasheras (now at BNL), to be published

Single Diffractive losses in collision 50+50 TeV



- Differential cross-section $\frac{d\sigma}{d\delta_p} = \frac{a_{sd}}{\delta_p}$ with $\delta_p = [\delta_{cut} = \frac{1}{s}, 0.15]$ and $a_{sd} = 0.7$ mb, integral $\sigma_{sd} = 15$ mbarn at VLHC.
- With increasing $s = E^2_{CM}$ only δ_{cut} changes
- Look at losses in the dispersion supressor - next slide

Single Diffractive losses in collision - continued

It can be shown that with a constant pipe section and a centered beam, the losses per meter in the dispersion suppressor are given by

$$\dot{n}_{sd} = \mathcal{L} a_{sd} \frac{D'}{D} \text{ with } D \text{ in meter} \tag{15}$$

Using $(D'/D)_{max} = 7 \times 10^{-2}\ \mathrm{m}^{-1}$ (the LHC value)

$$\dot{n}_{sd} = 5 \times 10^{5} \text{ proton s}^{-1}\mathrm{m}^{-1} \tag{16}$$

compared to a quench limit

$$\dot{n}_{q} = 5 \times 10^{5} \text{ proton s}^{-1}\mathrm{m}^{-1} \tag{17}$$

With unavoidable orbit and mechanical errors, the quench limit is passed.

POSSIBLE CURE : Build a dispersion $D \approx 0.5$ m in the straight section (outside the central part), collimate at $x \approx 20\sigma_\beta$ thus making a cut at $\delta_p = 2 \times 10^{-3}$.

– Might need longer straight sections (and interbeam distance ≈ 0.5 m)

– Would allow Single diffractive experiment.

References

[1] N. Catalan Lasheras, G. Ferioli, J. B. Jeanneret, R. Jung, D. I. Kaltchev and T. Trenkler, *Proceedings of the Symp. 'Near Beam Physics', Fermilab, 1997*, edited by D. Carrigan and N. Mokhov, p. 117 and CERN LHC Project Report 156, 1998 – quench levels, scattering.

[2] N. Mokhov, Energy Deposition working group summary, VLHC workshop, The Abbey, Lake Geneva , February 1999 – slide 13.

[3] J. B. Jeanneret, Phys. Rev ST Acc. and Beams, **1**,081001(1998) – slide 19.

[4] N. Catalan Lasheras, G. Ferioli and J. B. Jeanneret, *Proceedings of the EPAC98 Conference, Stockholm, 1998*, edited by S. Myers et al., p. 242 and CERN LHC Project Report 185, 1998 – preliminary analysis – slide 30.

[5] J. B. Jeanneret, CERN SL 92-44 (EA), 1992 – slide 32.

Summary

- Need optimum multiturn Betatronic and Momentum Collimation
- Collimation efficiencies look barely adequate – refine calculations first
- Collimation optics specified but not yet existing
- Single Diffractive losses downstream of experiments need local momentum collimation – would allow Single Diffractive Physics
- need long straight sections in both Collimation and Experimental Insertions